

# Folksonomies and clustering in the collaborative system CiteULike

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**Abstract.** We analyze *CiteULike*, an online collaborative tagging system where users bookmark and annotate scientific papers. Such a system can be naturally represented as a tripartite graph whose nodes represent papers, users and tags connected by individual tag assignments. The semantics of tags is studied here, in order to uncover the hidden relationships between tags. We find that the clustering coefficient reflects the semantical patterns among tags, providing useful ideas for the designing of more efficient methods of data classification and spam detection..

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Complex systems

The recent development of the World Wide Web is characterized by a growing number of online social communities. In many such cases, individuals provide bits of information - about either their tastes, opinions or interests - and software applications gather and organize them into a database, allowing the browsing of the whole information collected so. A class of such collaborative systems focusses on collecting users' online bookmarks with either a general approach or a more specialized one. In particular, some websites have been recently born to store user-generated scientific bibliographies.

In these systems, the elementary contribution, the “post”, is made of three ingredients: a user, an article and an annotation of it by a number of tags chosen by users. In exchange for this voluntary contribution, a user can browse others' bibliographies and annotations. Tags are an alternative classification method with respect to traditional taxonomies, where items belong to “taxa” represented as a tree-like set of categories: here, each category contains in turn a number of more specialized sub-categories, and so on until the desired resolution of classification is been reached. Instead, in tagging systems items are tagged by users characterized by diverse tagging strategies depending on a number of individual variables. The set of tag-resource relations in such a community is called a “folksonomy”.

Such communities are now extremely popular, storing hundreds of thousands posts and more. The tagging system we analyze here, *CiteULike* [1], has been built, at the time of our survey, by ca. 180000 references annotated by ca. 48000 tags supplied by ca. 6000 users. Our dataset includes about 550000 “tag assignments”: each assignment is a t-uple (user, resource, tag). The sequence of chronologically ordered tags, in particular, can be interpreted as a stream of words, to which one can applies the traditional statistical text analysis to uncover how human behavior affects it.

The statistical analysis of word occurrences in a written text has shown that word frequencies are power-law distributed according to the Zipf's law, according to which a large number of words appears in a text only a few times, while a few words occur orders of magnitude more often [2]. Such feature has been modeled by many models based on the preferential attachment principle, that is, the assumption that authors employ already used words with a probability proportional to the current word frequency. Moreover, it has been observed that the rate of new words decrease with the text-length [3], that is, the number of distinct word  $N_w$  in a text of length  $L$  scale as

$$N_w \propto L^\beta, \quad (1)$$

with  $\beta < 1$ . However, models in literature assume that new words are introduced at a constant growth rate, so that their total number, i.e. the vocabulary, is a linear constant of the total number of words (both new or repeated ones) used so far [5, 4, 6].

Yet, to discover the semantical properties of *CiteULike*, one rather represents it by means of the network formalism, which proved fruitful in the analysis of many natural and social phenomena involving unsupervised interacting units: in a network perspective, elementary interacting agents or objects are represented by nodes,

interactions by edges connecting them. The widespread success of such approach has been triggered by the discovery that many networks instances one encounters in reality share common statistical properties with no external tuning. For example, the degree  $k$ , that is, the number of edges pointing to a node, follows in many cases a broad distribution  $P(k)$  with long tail decaying algebraically as

$$P(k) \propto k^{-\gamma}, \quad (2)$$

with  $\gamma < 3$ . If edges have varying intensities, each of them is attached a weight  $w$  representing its intensity; accordingly, a node is characterized by its *strength*, equal to the sum of the weights of edges pointing to it. The distribution of *weights*, too, is power-law distributed in many real weighted network instances. Furthermore many such networks exhibit a strong transitivity, i.e. with high probability, the neighbors of a node are themselves connected by an edge, with respect to purely random realization of a network with equal number of nodes and links. Networks sharing the above properties are currently named “complex networks” [7].

The network approach has also been recently adopted to analyze the semantical structure of tagging systems [11, 12, 13]. Tags can be represented by networks in different ways, in order to study how the behavior of users maps into the dynamical or topological features. A more recent stream of research deals with the organization of tags, which are implicitly linked by hierarchical and logical associations emerging despite the diversity of users as their number is large enough. The underlying semantical organization of tags reveals the dominant trends within a tagging community and allows to improve its navigability. Recently, algorithms have been introduced in order to infer a taxonomy of tags from a folksonomy [8, 9].

The statistical properties we observed in the *CiteULike* data are consistent with the findings obtained in similar surveys, confirming that tags in collaborative systems form complex networks indeed. Moreover, we have investigated how the underlying semantics of tags reflects on the topology of the network.

As a matter of facts, tags provided by users come with no explicit hierarchy beside the chronological ordering, leading authors to analyze the stream of tags as a text-like sequence of words. Interestingly, the time-ordered sequence of tags displays statistical properties already observed in written texts, such as the fat-tails in the word frequency distributions or the sub-linear vocabulary growth.

Our analysis confirms the sub-linear vocabulary growth observed in written texts. The number of distinct tags  $N(t)$  introduced by users after  $t$  assignments grows approximately as  $N(t) \propto t^{0.7}$ , as shown in figure 1 although the pace is slightly smaller than in other collaborative tagging systems already surveyed [10].

The frequency of tags, too, reported in 2, reminds that of words observed in written texts, algebraically decaying according to the Zipf’s law [2].

However, the sole frequency of tags as a function of time does not convey much information about the semantics, although it reflects the different centrality of associated concepts in the underlying knowledge organization. To investigate tag pair relations,

one has to represent the unit elements of a tagging system as nodes of a network.

The dataset we focus on can be naturally represented as a tri-partite network, where each node represents either a user  $u$ , a resource  $r$  or a tag  $t$ ; if a tag assignment  $(u, r, t)$  exists, an edge is drawn from  $u$  to  $r$ , and from  $r$  to  $t$ . Since in a single user's post a resource can be tagged more than once, one post can correspond to multiple tag assignments [12].

Although efficient algorithm have been developed to analyzed such tri-partite network [14], the heterogeneity of nodes discourages in general the application of traditional network methods, mainly conceived to deal with network connections representing peer-to-peer relationships. Thus, to study how tags are organized we chose to project the tri-partite networks on the tag space. As a result, the tag co-occurrence network we study is composed by nodes representing tags only, between which an undirected edge of weight  $w$  is drawn if  $w$  distinct resources are labeled by both tags.

The resulting network displays some of the typical features of weighted scale-free networks. We have measured the distribution of the sum  $s$  of the weights of edges pointing to a given node, or the *strength* of the node: such distribution  $P(s)$ , plotted in figure 3, exhibits a clear power-law decay  $P(s) \propto s^{-\gamma}$ , with  $\gamma = 2.04 \pm 0.02$  for large values of  $s$ . Interestingly, the heterogeneity of the observed nodes' weights does not necessarily reflects the centrality of corresponding concepts, that are supposed to be assigned together with a wider range of more specialized concepts, in the underlying hierarchy of tags. As it has been already shown [15], reshuffling the tag assignment in order to destroy the logical association among words does not change dramatically the shape of  $P(s)$ , which proves that the *weight* heterogeneity is more a consequence of frequency distribution broadness than of the varying roles of concepts in the semantical organization of the whole vocabulary.

Nevertheless, the tag co-occurrence network unveils some semantical feature of the underlying ontology if, instead of focussing on the properties of single nodes, one turns to the inspection of quantities involving its environment. An example of such is represented by the analysis of the neighbor average degree  $K_{nn}(k)$  of nodes with degree  $k$ , where the degree is the number of incoming edges of a node.

In our study we examined instead the clustering properties of the tag co-occurrence network through the clustering coefficient. Such coefficient  $C(k)$  counts the average density of triangles involving nodes with degree  $k$  or, in other words, the probability that the nearest neighbors of a node with degree  $k$  are in turn connected one to each other. This reads

$$C(k) = \frac{2 \sum_{i, k(i)=k} \sum_{j>h}^{1,k} a_{ji} a_{hi}}{N_k k(k-1)}, \quad (3)$$

where  $a_{ij}$  is 1 if a link exists between  $i$  and  $j$  and 0 otherwise, and  $N_k$  is the frequency of nodes with degree  $k$ . This quantity has been found to characterize most complex networks found in nature and society, where it takes substantially larger values with

respect to a purely random networks [16]. The properties of the clustering coefficient are often associated to the hierarchical organization of nodes [17].

Indeed, the clustering coefficient appears to encode a signature of semantical relations between words. As represented in figure 4, the clustering coefficient  $C(k)$  in *CiteULike* decays algebraically for large values of the degree  $k$ , according to  $C(k) \propto k^{-0.64}$ . However, the clustering value displays an apparent fluctuation at  $k = 443$ . By inspecting the nodes corresponding to such value, one discovers that the sharp rise taking place at  $k = 443$  corresponds to a non-existing resource labelled by 444 distinct uncorrelated randomly chosen tags, which mimics the a spam contribution to the collaborative systems.

One is led thus to conjecture that the overall semantical organization of concept represented by tags is encoded in a characteristic behavior of the clustering coefficient  $C(k)$ , so that tags assigned in a semantically inconsistent way fall far away from this behavior. To verify such conjecture, we have performed the same statistical analysis after removing from the data set the tag assignments related to the spam-like page. As shown in figure 4, after the removal the clustering coefficient follows a more regular behavior, confirming that the strong fluctuation observed above was due indeed to the presence of a single meaningless set of assignments involving a single resource. Tags assigned only to the spam resource form a complete co-occurrence network, so that their clustering coefficient is equal to 1.

Thus, the behavior of clustering coefficient of the tag co-occurrence networks can be used as a test for models representing the tag semantical organization or, equivalently, how users choose tags when annotating a resource. As noted in literature [8], users typically use tags hierarchically, labelling a resource by tags related to the same topics but with different generality, adding more specialized tags as the number of collected resources grows.

On a very basic level, we have tested how such hierarchical tagging, affects the topology of the tag co-occurrence network by a simple toy model defined in the following. Let us assume that tags are organized on a taxonomy, that is, a tree-like structure stemming from a seed node, where each node corresponds to a tag and is an offspring of another tag belonging to the same branch of knowledge with higher generality. At discrete time steps, a new post is added to the system, with a new resource and 2 tags. The first tag can be a new one, with probability  $p_g$ : in such case, the new tag is an offspring of a tag randomly chosen among the already employed ones. Otherwise, the first tag is chosen at random among the already employed ones. The second tag is either chosen at random from within the whole set of used tags or, with probability  $p_b$ , it is chosen according to hierarchy: in such case, the second tag is drawn at random among the nodes that lie on the shortest path length from the first tag to the seed node on the tree-like taxonomy.

The tag co-occurrence network resulting from the above algorithm share some features of the *CiteULike* one, if we assume a time-dependent  $p_g$  which reproduces the sub-linear vocabulary growth observed in reality, and by a suitable choice of the

parameter  $p_b$ , which mimics the relevance of hierarchy in tagging activity. To reproduce the growth rule, we have set

$$p_g(t) = At^{-B} \quad (4)$$

and imposed that

$$\int_1^{N_{res}} p_g(t) dt = N_{tag} \quad (5)$$

and

$$N_{tag} = N_{ass}^\beta, \quad (6)$$

where the number of resources  $N_{res}$ , the number of tag assignments  $N_{ass}$ , the number of tags  $N_{tag}$  and  $\beta$  are set to the same values they take in *CiteULike*. As a result, this yields  $A = 5$  and  $B = 0.3$ .

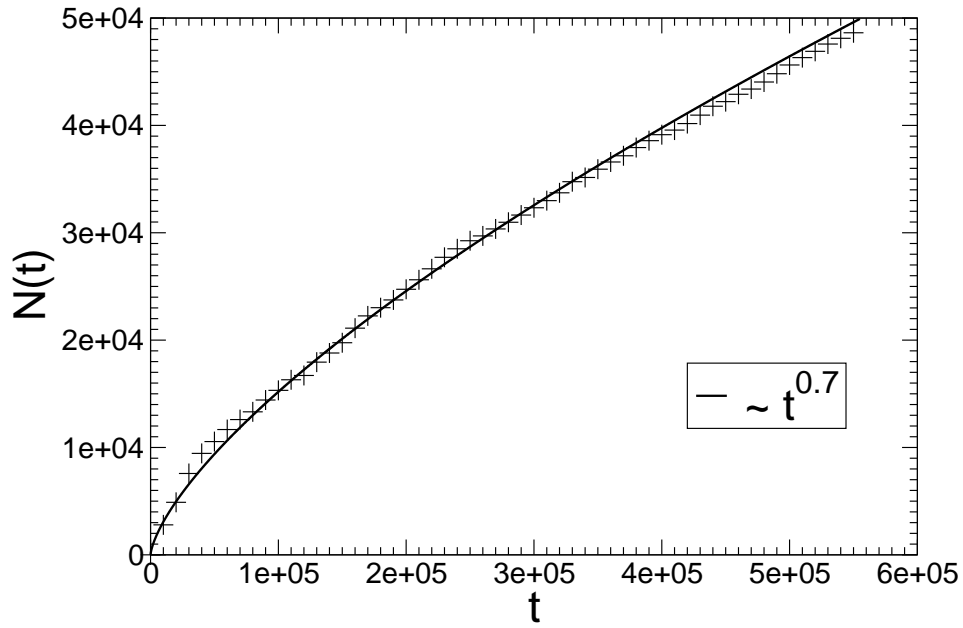
As shown in figure 3, the strength distribution  $P(s)$  of tags is a scale-free one with a good agreement with reality in the decaying exponent for large values of  $s$  if one sets  $p_b = 0.25$ . For such choice of the parameter, the clustering coefficient reproduces qualitatively the algebraic decay observed in *CiteULike*, as shown in figure 5, although the absolute value differs of orders of magnitude.

We have found, thus, a simple model that captures the complex features of a tag co-occurrence network issued from the dataset describing an online collaborative tagging system, *CiteULike*. In particular, by assuming that users label resources by hierarchically associated tags, the probability distribution of nodes' strength is reproduced for a suitable choice of the parameters. Moreover, the model reproduces qualitatively the decaying asymptotic behavior of the clustering coefficient  $C(k)$ . Such quantity encodes a signature of the semantical organization of concepts represented by tags, so that malicious or meaningless tag assignments can be detected by inspecting the perturbation to the clustering coefficient they generate. Establishing a relationship between clustering and semantics may suggest tools and algorithms for technological tasks such as automatic categorization of resources, recommendation and spam detection techniques.

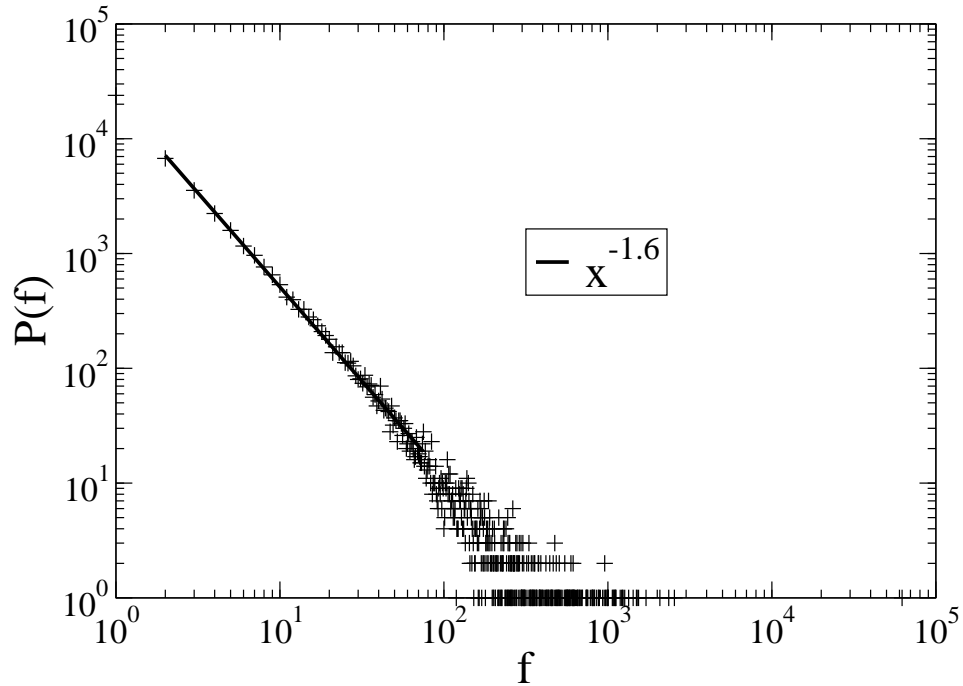
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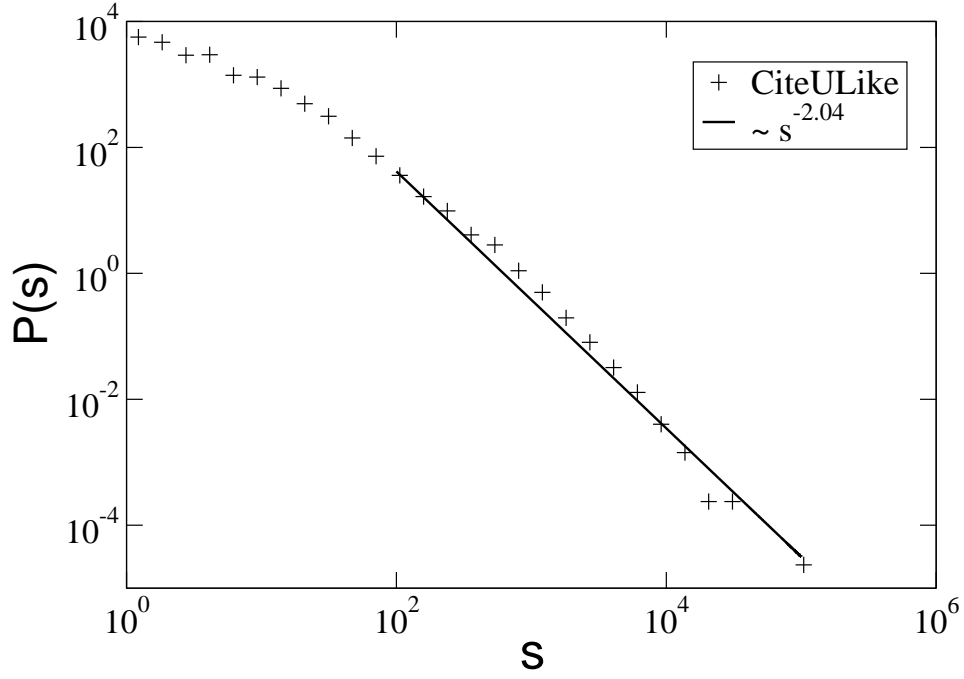
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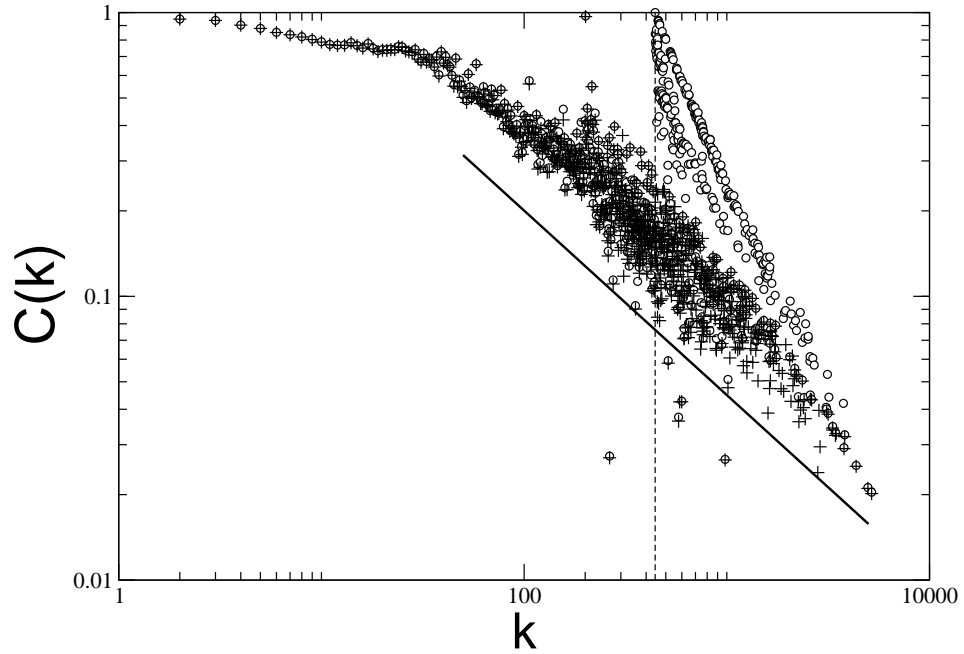
**Figure 1.** The number of tags  $N(t)$  as a function of time  $t$ , where time is measure in chronologically ordered tags assignments (plus symbols). Solid line represents  $t^{0.7}$  for a comparison.



**Figure 2.** The statistical distribution  $P(f)$  of tag frequencies  $f$  (plus symbols). Solid line represents  $f^{-1.6}$  for a comparison.

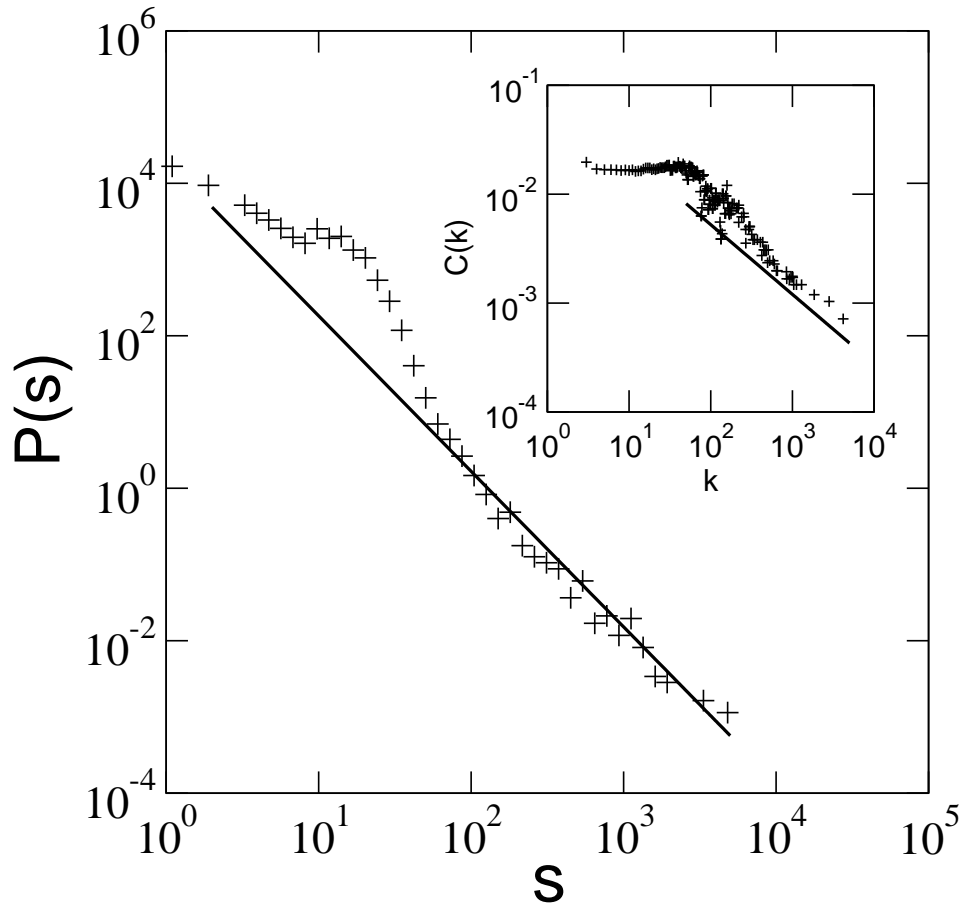


**Figure 3.** The distribution  $P(s)$  of the node strengths  $s$  in the tag co-occurrence network. The best fitting power-law exponent, represented by the solid curve, yields  $\gamma = 2.04$ .



**Figure 4.** The clustering coefficient  $C(k)$  of the tag co-occurrence network as a function of the nodes' degree  $k$  before (circles) and after (plus symbols) the removal of a spam post from the dataset. The solid line represents a decay  $k^{-0.64}$  and the dashed vertical ruler is set at  $k = 443$ .





**Figure 5.** Main plot: the strength distribution in the co-occurrence network derived from the model with  $p_b = 0.25$  (plus symbols); the solid line represents the decay  $s^{-2.04}$  for a comparison with real data. Inset: the clustering coefficient in the co-occurrence network derived from the model with  $p_b = 0.25$  (plus symbols). The solid line represents the decay  $k^{-0.64}$  for a comparison with real data.

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